Coupled Ocean-Atmosphere Dynamics and Predictability of MJO's

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LONG-TERM GOALS

Our long-term goal is to develop a coupled ocean-atmosphere model that has significant and quantified skill in predicting the evolution of Madden-Julian Oscillations (MJO's), which is highly relevant to ONR long-term objectives. This requires developing a better understanding of the sensitivities of the atmospheric circulation associated with MJO's to small-scale SST anomalies, regional-scale SST anomalies, the diurnal cycle, surface waves, upper-ocean mixing, and various other aspects of ocean-atmosphere feedbacks.

OBJECTIVES

The objectives and immediate scientific goals of the proposed research are:

1. *Develop and test the Scripps Coupled Ocean-Atmosphere Regional (SCOAR) model for MJO predictability and feedback process studies;*
2. *Develop and test a WRF-ROMS regional coupled model for MJO predictability and feedback process studie;*
3. *Test the NCAR CCSM coupled model for MJO predictability and in feedback process studies.*

APPROACH

We are working as a team to study MJO dynamics and predictability using several coupled models in the Indo-Pacific sector as team members of the ONR DRI associated with the DYNAMO experiment in the Indian Ocean. This is a fundamentally collaborative proposal that involves Miller and Waliser as well as Dr. Hyodae Seo of the Woods Hole Oceanographic Institution, Prof. Ragu Murtugudde of the University of Maryland, and Dr. Markus Jochum of NCAR. The results presented here include work by all the team members and their students (Mr. Aneesh Subramanian, SIO; Mr. Ankur Gupta, SIO) and research staff (Xianan Jiang, JIFRESSE), because we have discussed, instigated and synthesized each others' research activities and results by keeping in close contact via email and by meeting at various conferences during the past year. Additionally, through Waliser's role as co-chair of both the WCRP-WWRP/THORPEX YOTC Science Team and the MJO Task Force (www.ucar.edu/yotc/mjo.html), we work to leverage from those activities as well

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as to make sure our research outcomes are positioned to contribute to the overall objectives of those programs.

The primary questions we are addressing are:

1) Do the effects of mesoscale SST on the surface fluxes of heat and momentum introduce significant changes in the amplitude, structure, wavenumber and frequency of the MJO's?

This can be addressed by running models in both coupled and uncoupled mode and comparing the structures of the MJO's produced. Our theoretical work with a linear, barotropic, coupled model (Zhou and Murtugudde, 2009) demonstrates that the coupled system can respond to mesoscale SST anomalies indicating that high resolution coupled models may be crucial for answering this question accurately. The focus here is on how oceanic mixed layer coupling with the atmospheric boundary layer transfers heat and energy to the overlying large-scale atmospheric MJO dynamics, and then on how changes to the mixed layer induced by diurnal cycle forcing and surface gravity wave processes alter these effects.

2) What are the consequences on the predictability of regional MJO development when mesoscale ocean-atmosphere coupling is allowed to influence the evolving MJO?

Does the intrinsic variability (e.g., atmospheric storms) in the domain increase with these mesoscale feedbacks present, thereby lowering the predictability of MJO regional response? Or do the boundary conditions and large-scale dynamics of MJO strongly control the regional response? These uncertainty issues can be quantified by comparing sensitivities to initial conditions, boundary conditions, and physics parameterizations using models in coupled versus uncoupled mode and in high-resolution versus coarse-resolution mode, for both perfect model experiments and runs compared with observed events.

WORK COMPLETED

Since the start of this current award in spring, 2010, we have contributed to the following subset of accomplishments of the multi-institutional team:

- **a.** Constructed a regional version of SCOAR (RSM-ROMS) in the Indo-Pacific sector (led by Seo, WHOI)
- **b.** Constructed a regional version of WRF in the Indo-Pacific sector (led by Murtugudde, UMd)
- **c.** Constructed a new version of SCOAR (WRF-ROMS) in the Indo-Pacific sector (led by Seo, WHOI)
- **d.** Run and analyzed SCOAR-RSM and SCOAR-WRF for several years to determine how well MJO's are simulated. (led by Seo, WHOI, with Gupta, SIO)
- **e.** Run and analyzed WRF-ROMS for several years to determine how well MJO's are simulated (led by Strack, UMd, and Seo, UH)
- **f.** Run and analyzed CCSM4 to determine how well MJO's are simulated (led by Subramanian, SIO, Jochum, NCAR, and Miller, SIO)

g. Analyzed how MJO's in CCSM4 are affected by a global change scenario of the 21st century. (led by Subrmanian, SIO and Jochum, NCAR)

h. Tested the sensitivity of CCSM3 to convective parameterizations (led by Zhou, Columbia, and Murtugudde, UMd)

i. Developed a mixed-layer budget analysis of the Indian Ocean based on ECCO, including the DYNAMO location, to serve as a baseline for the new observations (led by Waliser, JPL)

j. Attended ONR PI meetings associated with the DYNAMO experiment (led by Miller, SIO)

k. Conducted teleconference group meetings with the MJO Task Force (TF), refined the near-term objectives of that activity, and in June 2010 held a TF meeting and co-organized an MJO workshop joint with the CLIVAR Asian-Australian Monsoon Panel (led by Waliser, UCLA/JPL)

RESULTS

The following summarizes our most interesting and important results during the second year of collaborative research under this research project.

SCOAR and RSM MJO modeling

Our first year efforts for the MJO sensitivity tests led us to construct a new version of the SCOAR Model based on the Weather Research and Forecast (WRF) atmospheric model, in addition to the existing Regional Spectral Model (RSM), coupled to the Regional Ocean Modeling System (ROMS). The primary motivation for this is to take advantage of the most up-to-date physics and parameterizations available in WRF. It has been shown that the Zhang-McFarlane (ZM) atmospheric convective scheme, modified to include the subgrid-scale convective momentum transfer and the dilute plume approximation (Neale et al. 2008), is critical in capturing the realistic tropical mean state and the improved tropical intraseasonal oscillations including MJOs in the CCSM4 (Zhou et al 2011a; Subramanian et al. 2011). A number of WRF sensitivity tests have confirmed that this is the case in the regional WRF model, and some of the results are briefly described here.

Our current effort is focused on configuring a tropical channel WRF-ROMS coupled model with 0.38° horizontal resolution. Figure 1 shows the model domain and the October-March (2005-2009) averaged 10-meter wind fields (U10) from the observations and WRF-only run. The WRF with the modified ZM produces a relatively better mean state in surface winds (Figure 1) compared to the one with other convective parameterizations previously used (not shown), although the intensity of the easterlies in the equatorial Indian Ocean is underestimated. With this setup, we want to assess the extent to which the WRF model captures the wavenumber-frequency characteristics of the observed boreal winter tropical intraseasonal variability.

Figure 2 compares the observed and simulated wavenumber-frequency spectra of the symmetric component (2.5°N-10°N) of the outgoing longwave radiation (OLR) and U10. The tropical channel WRF contains the enhanced spectral density in OLR and U10 fields over the broad band of the planetary wavenumbers k=1-4 and the frequencies w=0.006~0.055 cpd (18 to 166 days), which is in reasonable agreement with the observations. The model also features an enhanced coherence in

wind and convection fields over the observed MJO wavenumber-frequency bands as well as along the dispersion curve of the equatorial Kelvin waves.

Figure 3 illustrates the filtered OLR and U10 to pass the dominant MJO-related wavenumber and frequency bands in one particular year. The OLR and surface winds tend to propagate at roughly 5.9 m/s eastward with a phase lag. The westerly wind anomaly leads the suppressed convection, followed by the easterly anomaly leading to the enhanced convection. However the maxima in spectral power of the simulated OLR and U10 tend to be located systemically in the too low frequency band than what the observations suggest. The coherence squared between the simulated wind and convection is also much weaker than the observations, with the less obvious phase relationship within the eastward propagations in the model.

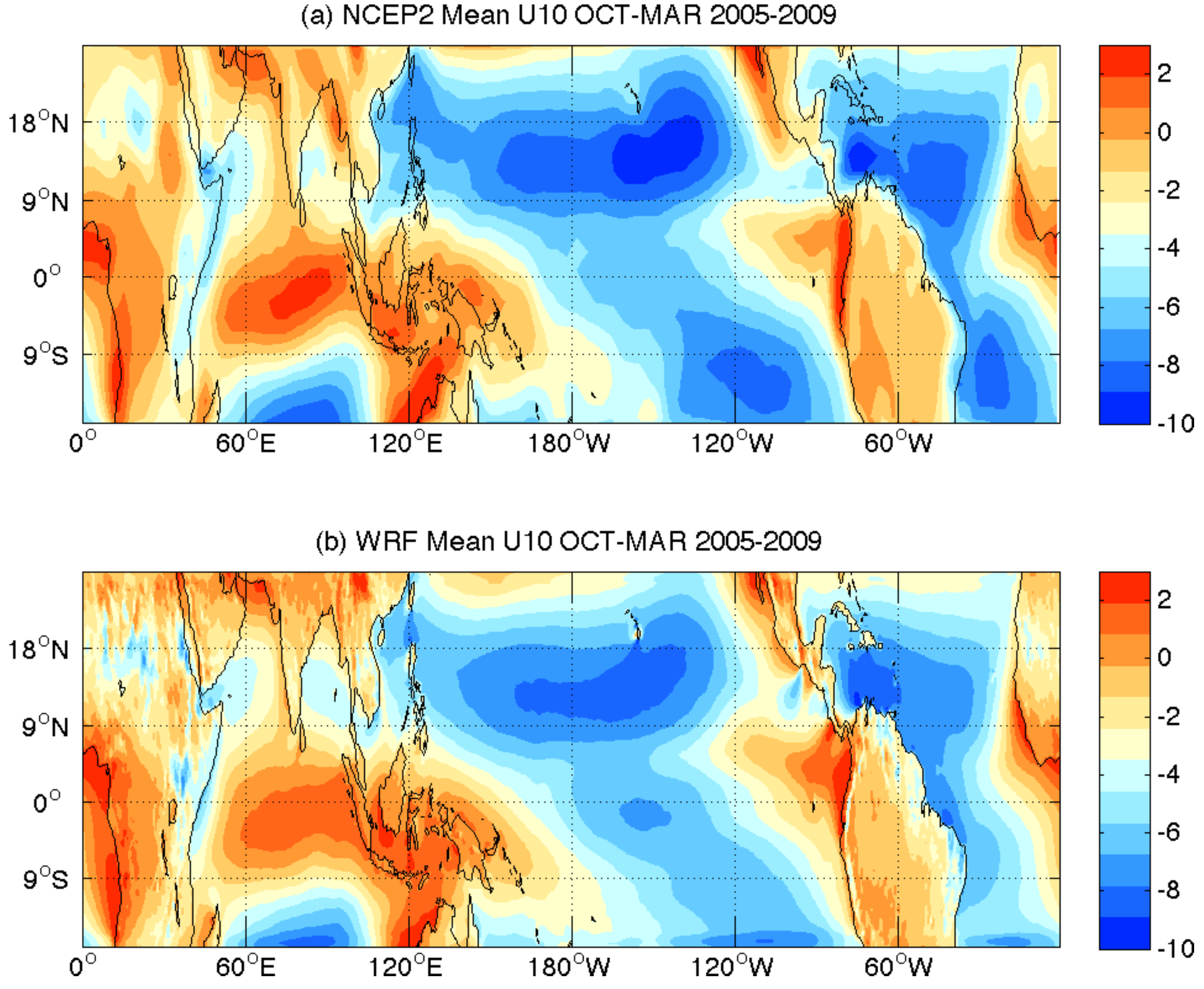

Figure 1. October-March (2005-2009) averaged surface 10-meter wind (U10) from (a) NCEP Reanalysis-2. (bottom) and (b) the WRF model simulation with the modified Zhang-McFarlane convective scheme.

These shortcomings in the WRF-only simulations will be a topic of our next step. The role of air-sea coupling will be assessed using the WRF-ROMS coupled model in improving the phase relationship and coherence between the convection and wind fields compared to the uncoupled WRF simulations. We plan to perform a variety of sensitivity tests with different ocean mixed layer resolutions (up to 2-3 meters depth in the mixed layer) and frequencies of diurnal coupling (daily to hourly). Specifically, we will examine 1) how the diurnal variability in the mixed layer

temperatures affects the phase lag and coherence between the intraseasonal anomalies in wind and convection associated with MJO and 2) how the surface heat and momentum fluxes play a role in conjunction with the improved ocean mixed layer processes in the evolution of simulated MJO.

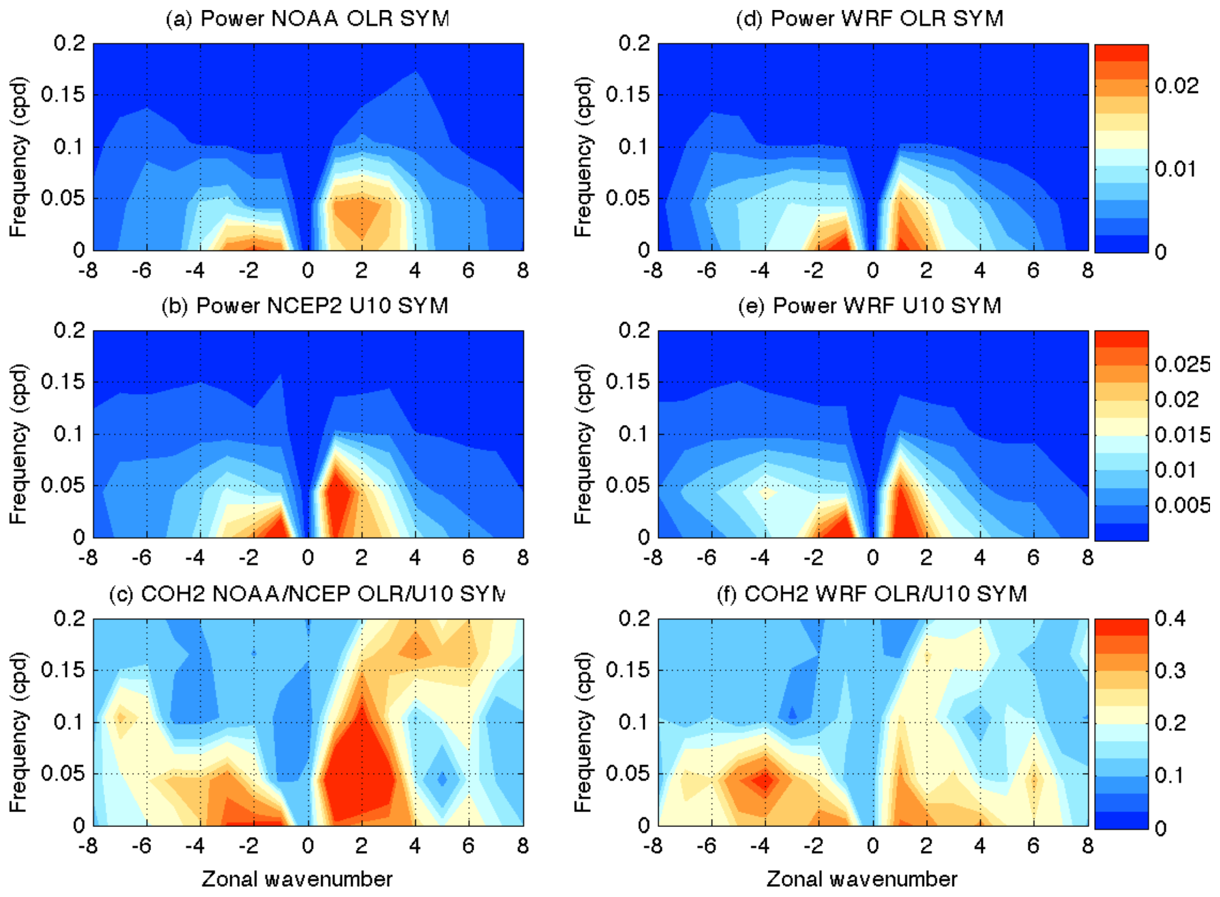

Figure 2. (Left) October-March (2005 to 2009) wavenumber-frequency spectral density of the symmetric component (2.5N-10N) of (a) NOAA OLR (W^2/m^4) and (b) NCEP U10 (m^2/s^2). (c) Coherence squared between OLR and U10. (Right) As in (left) except from the WRF simulation.

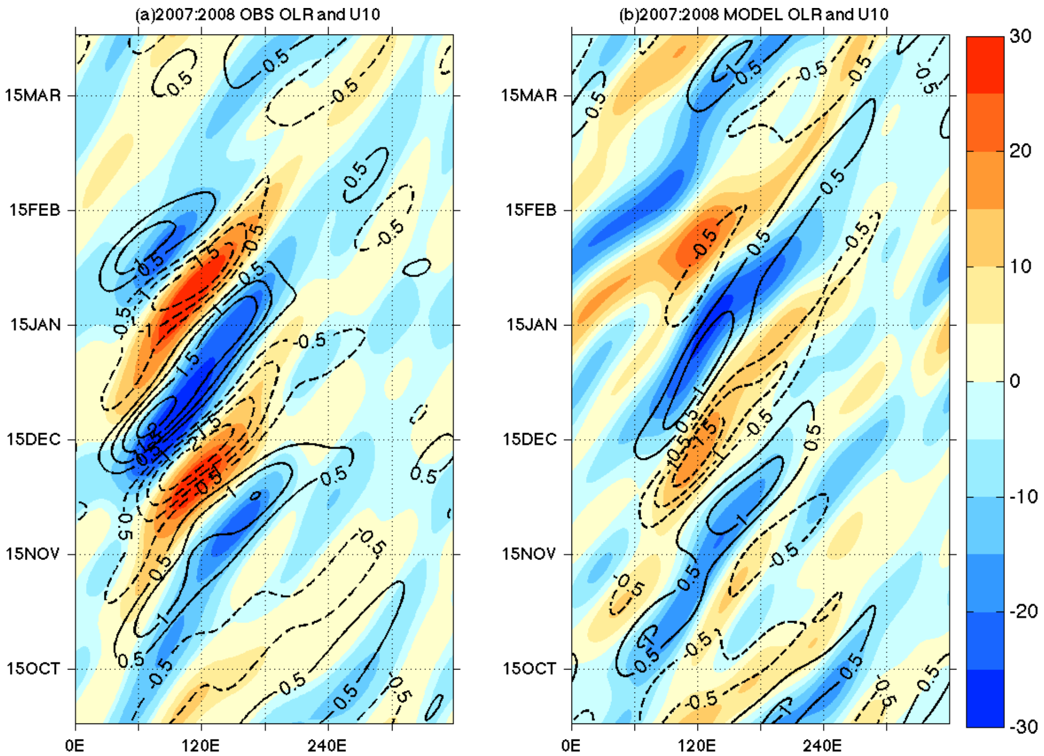

Figure 3. (a) Filtered (k=0~8, w=0.006~0.055 cpd, 18-166 days) NOAA OLR (shading) and NCEP U10 (contours). (b) As in (a) but from the model. The negative wind anomalies are show in dashed contours (CI=0.5m/s) CCSM MJO modeling

We completed our initial assessment of the ability of the Community Climate System Model-4 (CCSM-4) to represent the MJO. The results are now in press (Subramanian et al., 2011) in the special issue of *Journal of Climate* devoted to the recent release of CCSM4.

We used the US CLIVAR MJO Working Group prescribed diagnostic tests (Waliser et al., 2009) to evaluate the model's mean state, variance and wavenumber-frequency characteristics in a 20-year simulation of the intraseasonal variability in zonal winds at 850 hPa (U850) and 200 hPa (U200) and Outgoing Longwave Radiation (OLR). Unlike its predecessor, CCSM4 reproduces a number of aspects of MJO behavior more realistically.

CCSM4 produces coherent, broadbanded and energetic patterns in eastward propagating intraseasonal zonal winds and OLR in the tropical Indian and Pacific Oceans that are generally consistent with MJO characteristics (Fig. 4). Strong peaks occur in power spectra and coherence spectra with periods between 20-100 days and zonal wavenumbers between 1 and 3 (Fig. 5). Model MJO's, however, tend to be more broadbanded in frequency than in observations. Broadscale patterns, as revealed in combined EOFs of U850, U200 and OLR (Fig. 6), are remarkably consistent with observations and indicate that large-scale convergence-convection coupling occurs in the simulated MJO (Fig. 7).

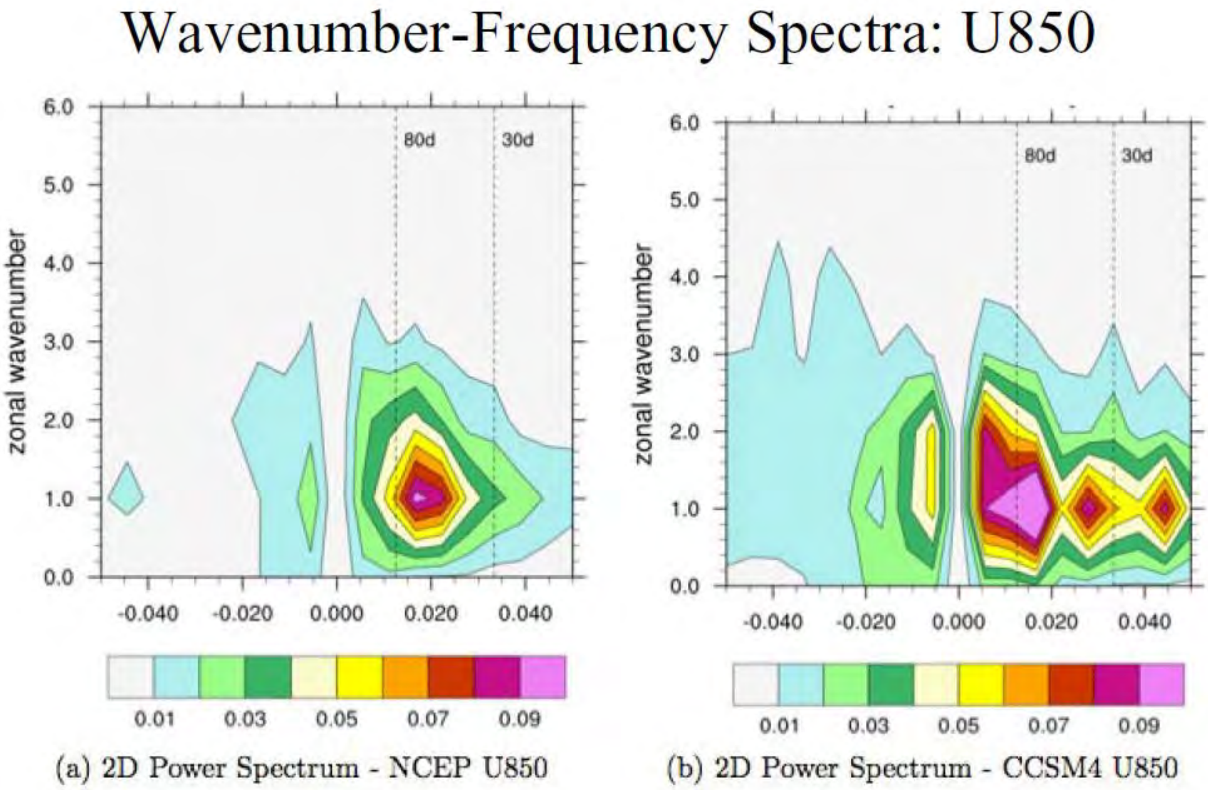

Figure 4. November-April wavenumber-frequency spectra of 10N-10S-averaged daily zonal 850 hPa winds of (a) NCEP (1981 - 2000) and (b) CCSM4 (20 years run). Individual spectra were calculated for each year, and then averaged over 20 years of data. Only the climatological seasonal cycle and time mean for each November-April segment were removed before calculation of the spectra. Units for the zonal wind spectrum are m^2/s^2 per frequency interval per wavenumber interval. The bandwidth is (180 days)$^{-1}$.

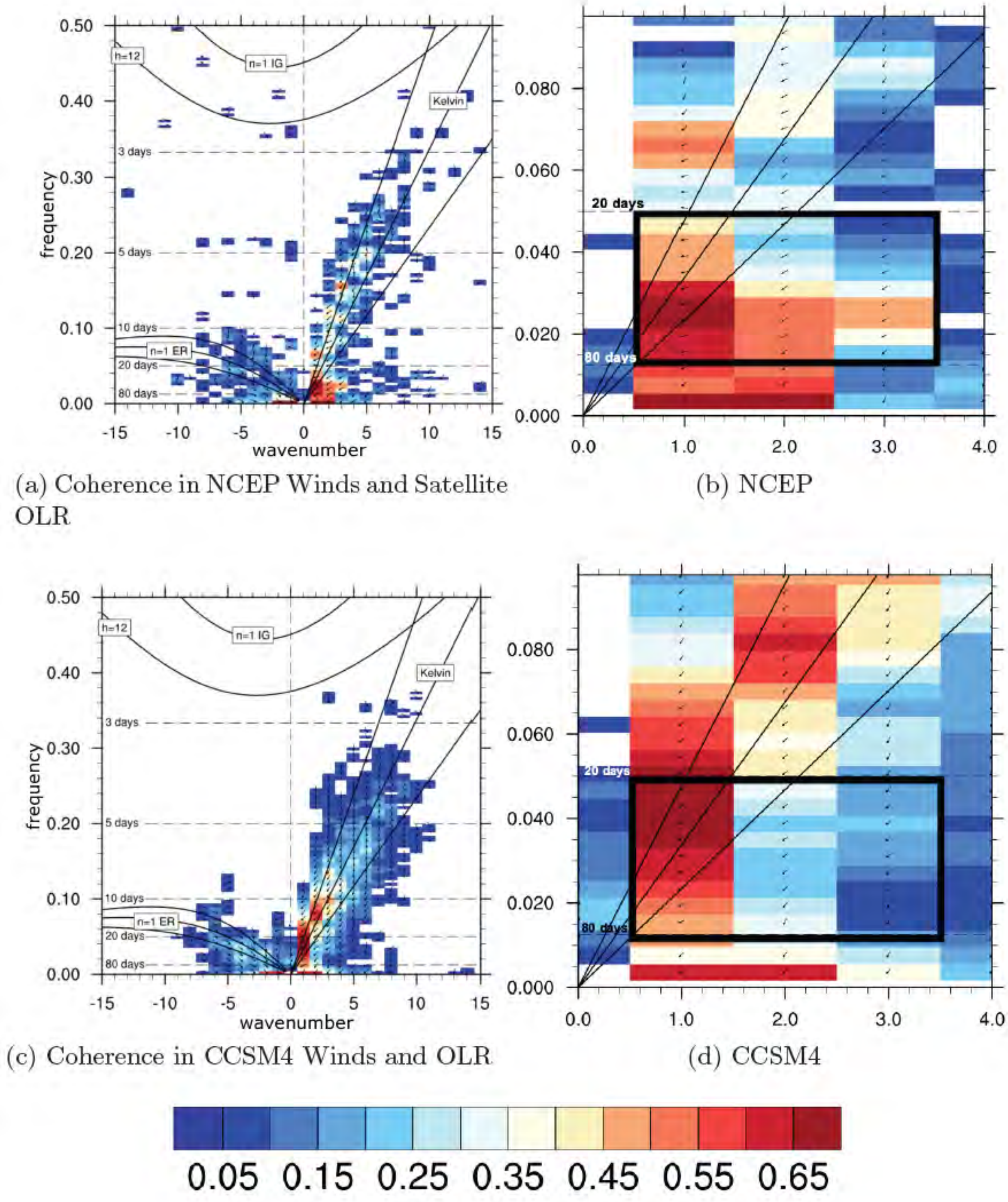

Figure 5. Coherence squared (colors) and phase lag (vectors) between zonal winds at 850 hPa winds and OLR are shown for (a) NCEP winds and satellite OLR (c) CCSM4 winds and OLR; (b) and (d) are expanded views of the MJO-relevant parts of the spectra. Only the symmetric spectra are shown here. Cross spectra are calculated using daily data during all seasons on 256-day-long segments, with consecutive segments overlapping by 206 days. Colors represent coherence squared between OLR and U850, and vectors represent the phase by which wind anomalies lag OLR anomalies, increasing in the clockwise direction. A phase of 0 is represented by a vector directed upward. Dispersion curves for the (n = -1) Kelvin, n = 1 equatorial Rossby (ER) and (n = 1) Inertia-Gravity waves corresponding to three equivalent depths (h = 12, 25, and 50 m) in the shallow water equations are overlaid (black contours). MJO is defined as the spectral components within zonal wavenumbers 1 to 3 and having periods 20 to 80 days as marked by the black box in the right panels.

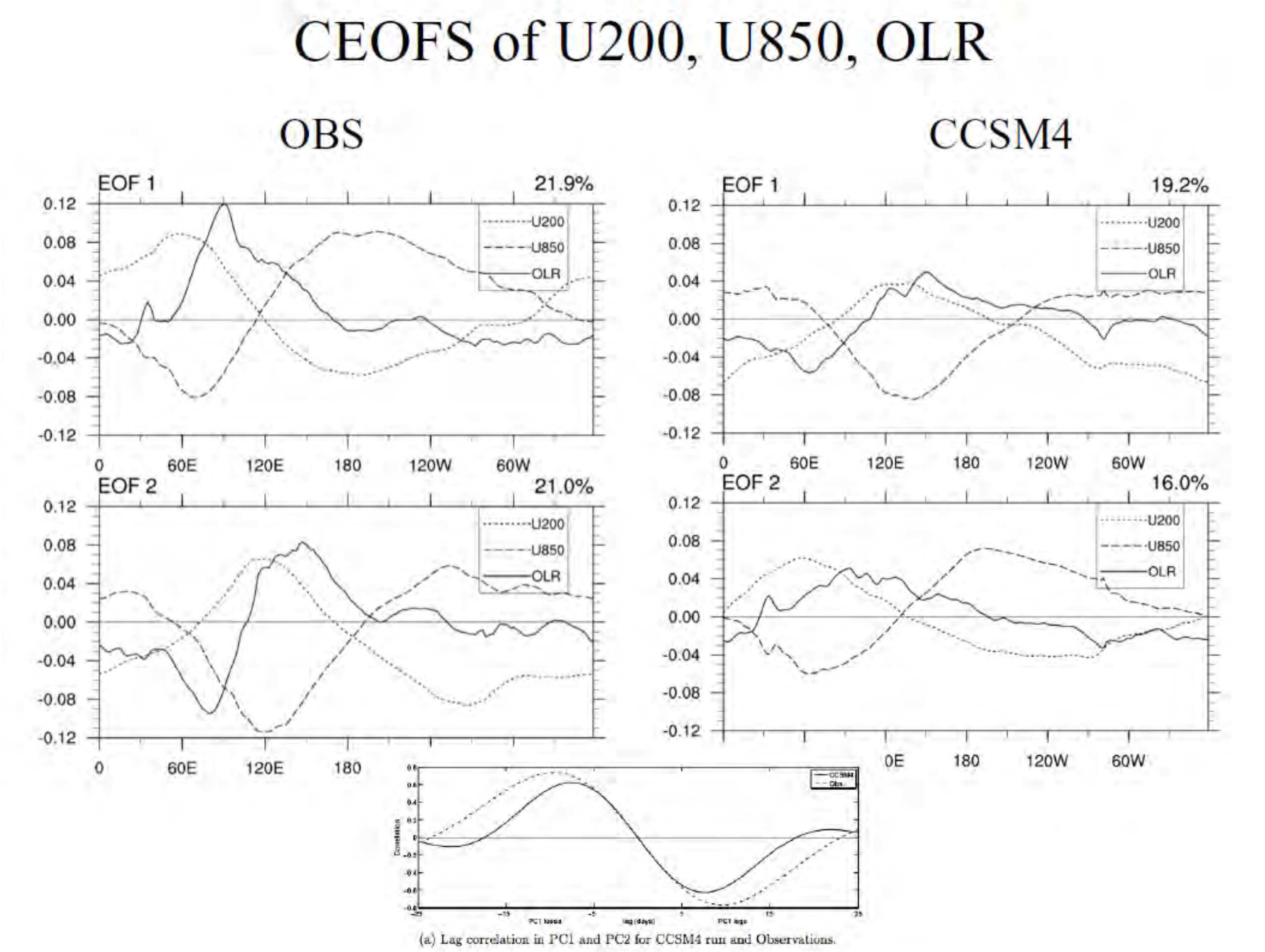

Figure 6. All-season multivariate first and second combined EOF (CEOF) modes of 20-100 day 15S-15N-averaged zonal wind at 850 hPa and 200 hPa and OLR from (left) NCEP and OLR from the NOAA satellite for 1980 – 1999 and (right) the 20 yr CCSM4 run. The total variance accounted for by each mode is shown in parenthesis at top of each panel. (Bottom) Lag correlation between PC1 and PC2 of Multivariate EOF analysis of the intraseasonal zonal winds at 850 hPa, 200 hPa and intraseasonal OLR anomalies from the CCSM4 run and the observations.

Relations between MJO in the model and its concurrence with other climate states are also explored. MJO activity (defined as the percentage of time the MJO index exceeds 1.5) is enhanced during El Nino events compared to La Nina events both in the model and observations. MJO activity is increased during periods of anomalously strong negative meridional wind shear in the Asian Monsoon region, and also during strong negative Indian Ocean Zonal Mode states, in both the model and observations.

We have also studied the response of the MJO in the model to anthropogenic climate change. We have examined the changes in frequency and amplitude of the MJO in the 21st century projections (Representative Concentration Pathways) for the 8.5 W/m2 forcing scenario compared to the 20th century simulations of the same. Changes in the mean and variability of the various atmosphere and ocean related fields such as the lower and upper level winds, precipitation, latent heat flux and surface temperature were studied. Comparison of the mean fields in the tropical zonal winds do not show any significant increase in mean global zonal 850 hPa winds.

Further studies will be made to link the changes in the frequency and amplitude of the MJO in the two climate regimes to changes dynamic or thermodynamic forcing. We plan to investigate the controlling parameters such as latent heat release, air-sea interactions, moist stability of the atmosphere on the MJO frequency and amplitude in the future climate scenario. This diagnosis will help us in understanding better what parameters control the strength and variability of the MJO in the tropics.

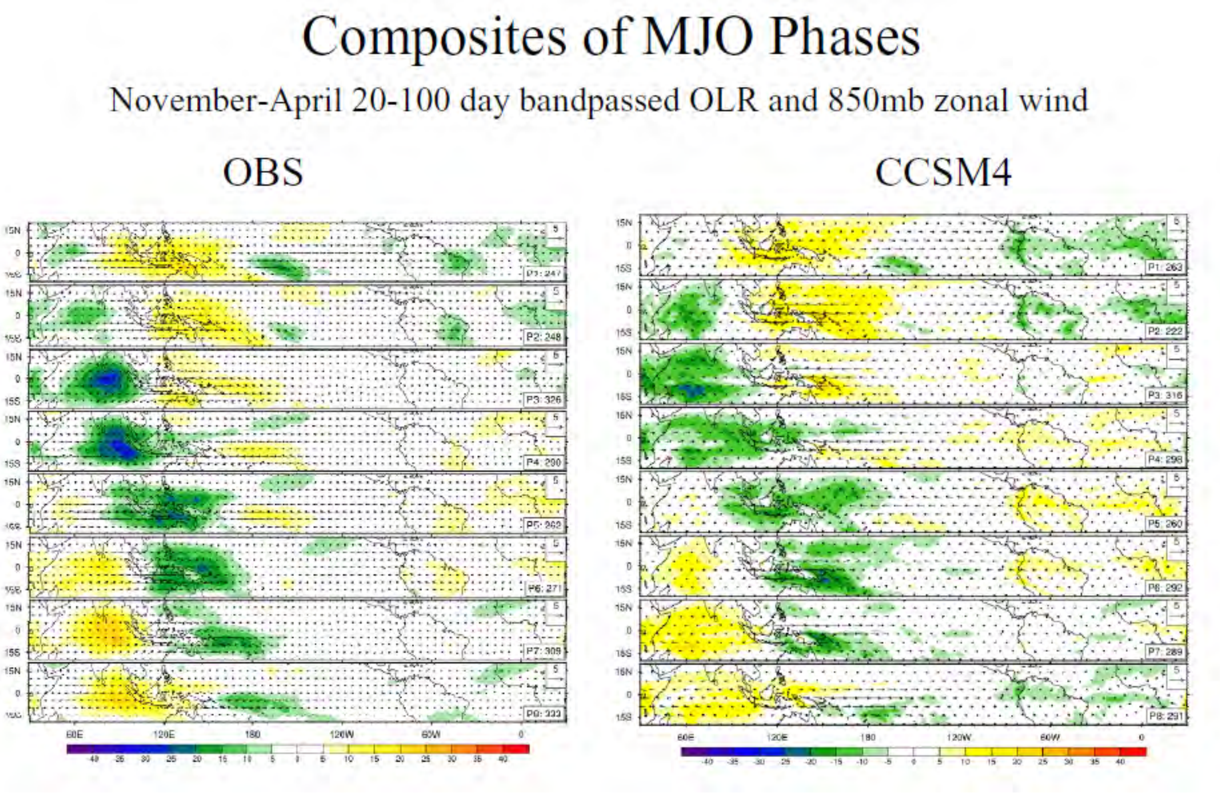

Figure 7. Composite November-April 20-100-day OLR (color, in Wm^{-2}) and 850 hPa wind anomalies (vectors) as a function of MJO phase for (left) observations from 1980-1999 and (right) the 20 year CCSM run. The reference vector in units of m/s is shown at the top right. The number of days used to generate the composite for each phase is shown to the bottom right of each panel.

IMPACTS/APPLICATIONS

We continue to discuss our research results with Dr. Mark Swenson, Chief Scientist, FNMOC, to determine how effort might eventually be used to improve forecasting of MJO activity for practical use by the Navy. COAMPS, with specified SST, is currently available for practical regional forecasts. We expect our research to better reveal how ocean-atmosphere mesoscale coupling can influence extended-range (1 week to 1 month) forecasts of MJO variations, what atmospheric convective and SST feedback processes must be included in the model, how strongly oceanic and atmospheric boundary conditions influence the skill of regional MJO forecasts, and what upper-ocean conditions need to be observed to best execute these practical forecasts. As COAMPS soon will also include interactive ocean capabilities with NCOM in real-time mode, our results will additionally provide a comparison to COAMPS skill levels and help point the way in dealing with various regional modeling limitations as well. Extended-range dynamical forecasts in regions influenced by MJO are based on a dynamical process that has potentially useful skill levels. These

forecasts are expected to be better than climatology and can contribute to establishing a smart climatology for these regions during times of MJO excitation. This forecast information can then be used in practical Naval operations planning. Dr. Swenson has agreed to continue to discuss our research results in the context of practical usefulness throughout the course of this research.

RELATED PROJECTS

WCRP-WWRP/THORPEX Activities

Waliser and X. Jiang been heavily engaged in developing and implementing a community model intercomparison project through a joint effort between the WCRP/WWRP-THORPEX MJO Task Force and GEWEX's Cloud System Study (GCSS). Its description is the 3rd subproject listed at: http://www.ucar.edu/yotc/mjo.html. The participants now number about 20 modelers signed up to contribute input. We plan to contribute to this as well.

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